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SUPERLATTICE OPTICAL ELEMENTS

P. J. Viccaro and E. Ziegler

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Introduction

The performance of state-of-the-art Layered Synthetic Microstructures (LSM)[1] or superlattices at x-ray energies even exceeding the soft x-ray domain is a promising sign that systems of this type may play an important role as x-ray optical elements in the energy region of interest to 6-GeV users. As will be discussed below, they are particularly attractive because of their large energy bandpass compared to crystals such as Si or Ge. In fact, they have been suggested recently as elements in high throughput large bandpass x-ray monochromators tunable in the interval of 5-30 keV.[2] For high flux applications, the hope is that LSM will prove to be stable in intense photon beams enabling them to filter out most of the heat load, that will reach narrow band pass crystal optical elements. A concurrent requirement is that their reflectivity in the X-ray region be large enough so that the gain in the bandpass will not be offset by an overall loss in flux. Indeed, measured reflectivities in some case are near 70% at the first Bragg peak indicating that a monochromator pair would have an efficiency of approximately 50%. While it is certainly desirable to improve this number, the increased bandpass means gains in total reflected power when compared to Si or Ge. Again, the effectiveness of these devices as optical elements such applications will depend on optimization of the reflectivities of LSM through adequate design optimization modeling and fabrication techniques.

Fundamental Aspects of LSM

An LSM consists of alternate layers of two materials A and B with thickness d_A and d_B respectively and a repeat distance $d=d_A + d_B$. For incident x-ray beams with energy $E(\mathrm{keV}) = \frac{12.4}{\lambda(\mathring{A})}$, reflections will occur at

Bragg angles θ given by the Bragg equation $n\lambda = 2d\sin\theta(1 - \delta_o/\sin^2\theta)$ where n is the diffraction order, and δ_o is decrement in the average refractive index. Strong peaks in the reflectivity will occur for momentum transfers perpendicular to the layers.

The minimum repeat distances achievable presently are near 20Å for carbon-tungsten (C/W) LSM. This means that the first order Bragg reflection for 20 keV X-rays occurs at approximately 30 mrad. While it places stringent requirements on the layer uniformity of the LSM, the shallow incident angle distributes the incident beam power over a larger surface of the device, thus reducing the power density. For vertical divergences of 0.2 mrad expected for 6-GeV radiation sources, this translates to LSM uniformity over a 20 cm length when it is placed at 25 m from the source.

The reflectivity for such a device is determined to a first approximation by the number of layers penetrated by the incident beam. If pairs of alternate layers are in phase over long correlation lengths normal to the layers, then one can expect to obtain predicted reflectivities. For C/W LSM these can be as high as 80-90% above 5 keV. The actual reflected power will depend on factors such as substrate flatness and interlayer roughness among others. Reflectivities smaller than the optimum are frequently encountered presumably because of inadequate control of these parameters.

The second property of this Bragg reflection is its energy bandwidth or bandpass which again depends on the number of layers participating in the reflection. In this case, neglecting absorption, the Scherrer equation for the Darwin width is applicable with $\Delta\theta \cot\theta \propto \frac{1}{N}$ for the first order peak, where N is the number of layer pairs participating in the diffraction peak. This is equivalent to $\Delta E/E = \frac{1.879}{N}$ for the first order Bragg peak. In the soft x-ray region, the bandpass is determined almost entirely by the absorption length of the incident radiation in a given LSM which is usually restricted to a relatively small number of pairs. For harder x-rays larger number of layer pairs are needed and narrower bandpasses can be expected. This also means that more stringent requirements on the correlation length are necessary over a large number of layers. As shown in Table III.8.1, for 100 layers, a bandpass of 2×10^{-2} is expected which is nearly three orders of magnitude larger than for the Si(111) reflection. In general, with state-of-the-art fabrication methods, LSM with more than 100 layer pairs are possible to fabricate.

Bandpass of an LSM as Function of Number of Penetrated Layers, N

$\Delta E/E$	N
1.9×10^{-4}	10000
1.9×10^{-3}	1000
1.9×10^{-2}	100
1.9×10^{-1}	10

However, it is not clear whether these systems maintain registry in the direction normal to the layer over large distances. If random differences occur in the spacings, reflectivity will decrease and bandpass will increase.(3) More interesting is the possibility to tailor the bandpass and total power reflected by introducing systematic gradients(4) in either the repeat distance or layered thickness i.e., by vertical grading of the LSM.

This area is the most promising from the point of view of 6-GeV optics where matching the multilayer bandpass allows efficient multicomponent systems.

Possible Applications and Necessary R&D

The obvious attractive properties of certain LSM devices from the point of view of 6-GeV radiation are the large reflectivities from 4-30 keV and their large and in principle adjustable bandpass in this region. Another important aspect is that the layers themselves are deposited on a substrate which in theory can be chosen to have good thermal conductivity for high heat load applications.

While these properties suggest several very relevant applications of LSM as optical elements for the 6-GeV synchrotron source, their success as optical elements will depend on several aspects of these systems which are not well understood at present.

The first is a complete understanding of the factors affecting reflectivity and bandpass of a given A/B superlattice. As mentioned, effects such as the degree of registry, roughness, etc. are important in determining the reflected power at a given energy. Despite existing modeling experimental characterization (x-ray diffraction, electron microscopy, etc.) of these effects it is clear that more has to be done to adequately describe LSMs.

A second perhaps more critical area involves the thermal stability of LSM under intense photon beams. The layered structure must be able to maintain its integrity at power loads of up to 2000 W/cm^2 peak power if they are to be used effectively as power filters. Admittedly, smaller load handling capabilities would be interesting but would limit the applicability of these devices. Some promising signs in this area are some preliminary results of conventional thermal loading of C/W LSM.[5,6] In all cases studied to present, the LSM maintains its superlattice structure upto 650-750°C. While this is a very positive result, nothing is known concerning the power loading properties of these and other LSM, in photon beams. High radiation flux damage experiments at 1 keV are in their initial stages.(7) However, research at the energies and fluxes expected from the 6-GeV synchrotron is essential.

Two important applications of LSM as x-ray optical elements are proposed in the 6 GeV program. The first of these is to use the device as a beam splitter and filter. It is obvious that if the incident beam is "white" then at a given incident angle θ, the reflected beam for the first Bragg peak would center around θ with a energy content determined by the band pass of the LSM. Note that for momentum transfers off the normal, the reflectance is weak. The device is similar to a mirror/beam splitter but with a higher degree of monochromatization.

A second application is one involving a pair of curved LSM operating a focusing monochromator. As suggested by Bilderback et al.(2) assuming that bandpasses can be tuned, then focusing can be accomplished on both elements allowing both vertical and sagittal focusing without sacrificing intensity. Band passes can be expected between 0.005 and 0.1 which can result in intensity gains of two orders of magnitude over Si.

Both applications would have immediate application for many of the 6 GeV beamlines discussed in Section III.3 if thermal stability and reflectivities are acceptable. More sophisticated elements will depend on the minimum repeat distance attainable for LSM.

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